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Enhancing Speech Discrimination Through Stimulus Repetition

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Purpose: To evaluate the effects of sequential and alternating repetition on speech-sound discrimination.

Method: Typically hearing adults' discrimination of 3 pairs of speech-sound contrasts was assessed at 3 signal-to-noise ratios using the change/no-change procedure. On change trials, the standard and comparison stimuli differ; on no-change trials, they are identical. Listeners were presented with 5 repetition conditions: 2 and 4 sequential repetitions of the standard followed by sequential repetitions of the comparison; 2 and 4 alternating presentations of the standard and comparison; and 1 repetition of the standard and comparison.

Results: Both sequential and alternating repetition improved discrimination of the fricative and liquid contrasts, but neither was clearly superior to the other across the conditions.

Conclusions: The results support previous findings that increasing the number of fricative and liquid stimulus presentations improves discriminability and extends the findings to natural speech stimuli. Further, the effect of repetition is robust: Both sequential and alternating repetitions improve speech-sound discrimination, and few differences emerge between the two types of stimulus repetitions. The results have implications for evaluating the strength of the internal representation of speech stimuli in clinical populations believed to have a core deficit in phonological encoding, such as children with hearing loss.

Key Words: speech perception, stimulus repetition, discrimination

Auditory discrimination of speech is more than simply a sensory and acoustic–phonetic phenomenon. Discrimination of speech sounds can be enhanced with multiple stimulus presentations (Holt & Carney, 2005, 2007). In other words, perception involves more than some percept of a compilation of acoustic features; rather, the robustness or detail of the internal representation of a stimulus varies with multiple opportunities to perceive the stimulus. The purpose of the present investigation was to investigate the sensory and neurocognitive mechanism behind this phenomenon by examining two potential routes to enhanced speech discrimination with multiple stimulus repetitions: one in which a stimulus is presented in succession, followed by consecutive repetitions of a comparison stimulus, and one in which the differing stimuli are presented in an alternating fashion, such that the contrast itself also is presented multiple times.

The ability to effectively communicate using spoken language relies on many factors ranging from accurately perceiving a speaker's message to intelligibly communicating one's thoughts to using appropriate pragmatic skills in discourse contexts (e.g., Moore, 2007). Each component of the human communication speech chain can be broken down into many subskills. Some minimal command of each subskill is required for effective communication. In the case of speech perception, different levels of auditory information processing are necessary for understanding speech (Aslin & Smith, 1988). In their review of perceptual development, Aslin and Smith proposed a useful framework for studying auditory perception that utilizes three structural levels of perception. In the first level—the *sensory primitives stage*—sensory stimulation is detected. In the second level—the *perceptual representations stage*—stimulation is transformed into a neural code that refers to meaningful objects or events. The events themselves result in a pattern of meaningful neural activity and, as such, can be discriminated from other potential stimulation, but they do not carry semantic meaning until the final stage. In the final

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level—the *higher order representations stage*—semantic interpretation is provided to the events. Although this hierarchical view is but one way to describe and investigate perception, it is widely used both in the auditory and vision literature and has even been applied to the development of affective expression perception (Walker-Andrews, 1997). Walker-Andrews described this developmental process as one of "perceptual differentiation" (p. 437), in which properties that make up the whole and potentially carry meaning are detected, and only later are they discriminated from each other and then recognized as units. In terms of speech perception, one must be able to detect speech in order to discriminate one sound from another. In turn, one must be able to distinguish among or between speech sounds in order to recognize words accurately.

That being said, discrimination of two speech sounds does not necessarily imply that phonetic categories are present for the two sounds and, as such, have linguistic meaning. A classic example of this comes from the infant speech perception literature. Eimas, Siqueland, Jusczyk, and Vigorito's (1971) seminal paper on 1- and 4-month-olds' ability to discriminate voice onset time categorically does not imply that neonates are discriminating the speech sounds phonetically (Jusczyk [1985, 1986] suggested that it is not until the infant discovers that there is a link between sound and meaning that the individual segments [phonemes or syllables] serve a linguistic function). In fact, discrimination probably is not even occurring at the level of the cortex. Moore and Guan (2001) showed that although the auditory brainstem pathway is relatively mature at birth, development of the cortex extends well beyond the newborn period. In fact, mature axons are only present in the most superficial cortical layer—the marginal layer—through at least 4.5 months of age (Moore, 2002). Although marginal layer axons likely play a role in driving the activity of cells deeper in the cortex during the first year of life, they carry little information about external auditory stimuli. Therefore, newborns' ability to discriminate many native and nonnative speech sounds (Eilers & Minifie, 1975; Eimas, 1975; Trehub, 1976; Werker, Gilbert, Humphrey, & Tees, 1981) is a good example of the fact that one can discriminate two inputs without having categories—in this case, phonetic ones—for that input. Analogous to this argument is a finding in the literature on affective emotion perception in infants, discussed previously. Walker-Andrews (1997) suggested that young infants who demonstrate discrimination of vocal and static facial expressions do so on the basis of feature differences. Only later in development could the infants in this study complete the same task using affectively relevant information. In other words, young infants did not have affective or emotion categories for discriminating the input but were able to discriminate the auditory or visual facial information using a different strategy.

Regardless of how an individual completes a speech discrimination task, the ability to discriminate two phonologically contrastive stimuli is important to the eventual formation of phonetic categories (if the individual does not have those categories yet) and to the ability to identify words. If the formation of highly detailed phonological representations is disturbed in some way (due to hearing loss, processing deficits, or other sensory or cognitive disabilities), it can have cascading effects on any task that taps the ability to form accurate neurocognitive representations of auditory signals. In other words, a breakdown or disturbance at any level can lead to delays in language, social, educational, and even emotional development (Carney & Moeller, 1998; Moeller et al., 2007a, 2007b). Although it is likely that information flows in a bidirectional manner, Aslin and Smith's (1988) hierarchical framework provides multiple points of entry for investigating speech-sound processing in both healthy and clinical populations.

It is important to form robust, highly detailed acoustic–phonetic representations of speech sounds for further processing. However, the field of speech perception (aside from research concerned with infant perception) primarily has focused on the sensory primitives and higher order representation levels resulting from sensory processing while often ignoring the detailed nature of the early perceptual representations level. One method for assessing the neglected middle level of information processing, in which sounds are discriminated from one another, is the *change/no-change procedure* (Sussman & Carney, 1989). During a test trial, listeners are auditorily presented with a sequence of nonsense syllables that either change midway through the string (e.g., /ra ra **la la**/) or remain identical (e.g., /ra ra ra ra/). The first set of stimuli presented are considered *standards,* and the second set of stimuli are *comparisons.* For example, in a change trial consisting of /ra ra la la/, the standard, *ra,* is presented twice followed by the comparison, *la,* which is also presented twice. The listener's task is to indicate whether the standard and comparison stimuli are the same or different using a developmentally appropriate behavioral response task, such as pressing a button. The methodology has been used with both adults and children but is particularly useful for testing young children who have the most limited language and auditory skills because it does not require an explicit linguistic response (although the concept of "same/different" must be understood). The procedure's validity and reliability have been demonstrated in adults and children with normal hearing (NH) as well as in those with hearing loss (Carney et al., 1991, 1993; Dawson, Nott, Clark, & Cowen, 1998; Holt & Carney, 2005, 2007; Osberger et al., 1991; Sussman, 1991, 1993; Sussman & Carney, 1989). However, until recently, it has been used under the assumption that the number of presentations of the stimuli on or within a given trial does not influence performance. Motivated by Viemeister and Wakefield's (1991) "multiple looks hypothesis," Holt and Carney (2005) directly assessed this assumption.

Viemeister and Wakefield's (1991) *multiple looks hypothesis* was developed to reconcile the contradictory findings in hearing that two time constants are involved in temporal integration or summation (when detection threshold improves with increased stimulus duration). Specifically, the authors proposed that rather than working as a long-term integrator, the auditory system quickly samples the incoming signal. Each sample provides the system with a 3- to 5-ms "look" at the signal. Each look can be stored in short-term memory and then can be selectively accessed and processed. Long-duration signals provide more opportunities to be sampled than shorter signals. Therefore, the longer a stimulus, the more looks available and the more likely that at least one look will be above the listener's detection threshold, resulting in better detection thresholds for longer stimuli than for shorter stimuli.

Repetition Effects on Speech-Sound Discrimination

Attempting to bridge the gap between basic psychophysical research on hearing with adults and speech perception, Holt and Carney (2005) applied and extended the assumptions of the multiple looks hypothesis to longer stimuli in a speech discrimination paradigm. Using the change/no-change procedure with NH adults, the authors assessed discrimination of three pairs of synthetic syllables (/pa/ vs. /ta/, /ra/ vs. /la/, and /sa/ vs. /ʃa/) at four signal-to-noise ratios (SNRs) using all possible combinations of one, two, and four repetitions of standard and comparison stimuli. The results suggested that discrimination sensitivity improved with more standard and comparison stimulus repetitions for the liquid and fricative comparisons (which were reanalyzed in a more recent study [Holt & Carney, 2007]). In this more recent study, Holt and Carney reported that 4- and 5-year-old children's speech-sound discrimination also was enhanced with more stimulus repetitions of the fricative contrast.

Holt and Carney (2005, 2007) suggested that stimulus repetition allowed listeners to form stronger, more robust perceptual representations of the speech sounds, thereby giving listeners the ability to better use the early sensory-based representation for comparison with another representation. These findings are consistent with current theories of speech perception (e.g., Trace [McClelland & Elman, 1986], PARSYN [Luce, Goldinger, Auer, & Vitevich, 2000], and Shortlist [Norris, 1994]), all of which involve the core concepts of *activation* and *competition* (e.g., Gaskell & Marslen-Wilson, 2002; Luce & McLennan, 2008; Luce & Pisoni, 1998; Marslen-Wilson, 1989). The *activation–competition* metaphor in speech perception refers to the process whereby multiple lexical representations that are consistent with the stimulus input are activated, resulting in competition for identification of the target by the other activated representations (Luce & McLennan). Further, these representations are activated *radically,* meaning that it is more than just the target representation and the representation of words that share forms or phonemes with the onset portion of the target that are activated and compete for identification; rather, representations that share similar acoustic–phonetic input with the target at any point throughout the word are activated in short-term memory, resulting in lexical competition. A stronger, more robust representation of the target word results in decreased competition from lexical competitors, which leads to more accurate and more efficient word identification. According to our preliminary data, sequential stimulus repetition appears to be one way in which to strengthen the early representation and reduce competition, at least in a nonsense syllable discrimination task. This does not necessarily imply that repetition of an input occurs in natural phonological category formation but, rather, that repetition potentially is one way to strengthen the early sensory representation such that discrimination can be enhanced.

Converging Support for Repetition-Induced Strengthening of the Early Representation: Repetition Suppression and Repetition Priming

Research on *repetition suppression* (the term used in the neurophysiology literature) and *repetition priming* (the term used in the cognitive psychology literature) also provides converging support for this view. In repetition priming or repetition suppression paradigms, the effects of stimulus repetition on changes in both brain activity and behavior are evaluated. In response to stimulus repetition, two complementary responses occur—one in the neural realm and the other in the behavioral realm. Neurophysiologically, centers in the brain generally show decreases in activation with stimulus repetition measured using positron emission tomography or functional magnetic resonance imaging (e.g., Cabeza & Nyberg, 2000; James & Gauthier, 2006; Schacter & Buckner, 1998; Squire et al., 1992; Wiggs & Martin, 1998). The actual area of decreased activation depends on the stimuli and the task required of the participant. In addition, electroencephalogram (EEG) recordings show reductions of induced gamma-band responses and phase synchrony between electrode positions, at least for familiar stimuli (e.g., Fiebach, Gruber, & Supp, 2005; Gruber, Malinowski, & Muller, 2004; Gruber & Muller, 2002). Further, repetition-induced changes have been noted in the event-related potentials of the EEG, which typically are manifested as a reduction in wave amplitude at or beyond 200 ms after stimulus onset (Henson, Rylands, Ross, Vuilleumeir, & Rugg, 2004; Gruber & Muller, 2005), although it can be earlier if no intervening stimuli are presented (see review by Grill-Spector, Henson, & Martin, 2006). Unfortunately for our purposes, most of the EEG work was done with visual stimuli (Monsell, 1985), and the studies that used auditory stimuli used different types of priming, such as semantic and riming (e.g., Radeau, Messon, Fonteneau, & Castro, 1998), which do not directly apply here.

In contrast to the neurophysiological data, behavioral responses—usually measured by reaction time or accuracy—improve with stimulus repetition (e.g., James & Gauthier, 2006; Roediger & McDermott, 1993; Schacter, Chiu, & Ochsner, 1993). This pattern of results has been reported for visual objects (e.g., Busch, Groh-Bordin, Zimmer, & Herrmann, 2008; Henson et al., 2004); visually presented text (e.g., Forbach, Stanners, & Hochhaus, 1974; Grant & Logan, 1993; Huber, 2008; Scarborough, Cortese, & Scarborough, 1977); spoken words (e.g., Church & Schacter, 1994; Orfanidou, Marslen-Wilson, & Davis, 2006; Schacter & Church, 1992); spoken pseudowords or nonwords (e.g., Graves, Grabowski, Mehta, & Gupta, 2008; Orfanidou et al., 2006; Rauschecker, Pringle, & Watkins, 2007); and spoken sentences (e.g., Hasson, Nusbaum, & Small, 2006). The results also have been demonstrated in investigations in which the stimuli are repeated once (Orfanidou et al., 2006; Scarborough et al., 1977) and when they are repeated two or more times (Forbach et al., 1974; Grant & Logan, 1993; Graves et al., 2008; Rauschecker et al., 2007). In general, more stimulus presentations result in more enhanced behavioral responses (faster reaction times and higher accuracy rates).

Many of the procedural aspects of the repetition priming and repetition suppression studies are different from the change/no-change procedure used by Holt and Carney (2005, 2007). The tasks used in repetition priming and suppression studies on spoken word recognition vary from making lexicality judgments (identifying whether a presented item is a word or not) to repeating the stimuli, whereas the change/no-change procedure uses a discrimination task with minimal auditory uncertainty. Also, the stimuli used in the repetition priming studies typically are more complex than those used in our earlier work on the change/no-change procedure (words, pseudowords, and sentences compared with nonsense syllables). And finally, the manner in which the repetition is carried out is different. In the repetition priming and repetition suppression work, repeated stimuli are presented with various temporal delays and sometimes with intervening stimuli (which are not necessarily contrastive with the target stimuli), whereas the stimuli in the change/no-change procedure are presented with a constant interstimulus interval in immediate succession. Although there are procedural differences and possibly different neural mechanisms at work between repetition priming and the change/no-change paradigms, similar behavioral results have been obtained: The response improves with additional opportunities to sample and process the stimuli before initiating a response.

Alternate Route to an Enhanced Early Representation

Although Holt and Carney (2005, 2007) suggested that discrimination improves by enhancing the internal representation of the stimuli with consecutive stimulus repetitions, which is supported by the repetition priming work, another conclusion is also possible. The change/no-change procedure consists of two components: multiple repetitions of the stimuli and an abrupt shift in the stimuli. Without investigating the influence of both components on the task, it is unclear whether one or both factors contribute to the observed improved discrimination. In other words, there could be multiple routes to enhanced discrimination: one in which the internal representation of each stimulus is enhanced with more sequential repetitions of stimuli (e.g., /ra ra ra ra la la la la/) and one in which the perception of the stimulus is enhanced by contrasting it with another stimulus through repetition of the change in stimuli (e.g., /ra la ra la ra la ra la/). This alternate hypothesis—that repetition of the contrast itself might enhance speech discrimination—is consistent, in some respects, with research on motor learning (e.g., Edwards & Lee, 1985; Wrisberg & Ragsdale, 1979).

While learning a motor task, individuals who practice the same sequence of movements under identical conditions demonstrate less transfer of learning than those who practice under varying conditions. Improved motor learning with practice variability is believed to be due to contextual interference (Battig, 1979). Contextual interference is high either when the learner must practice several new, related skills in the same session or when the conditions change within the same session. In contrast, low contextual interference occurs when a learner practices a single skill under one condition. Somewhat paradoxically, although high-contextual interference practice situations lead to more errors during practice, they also produce higher retention and transfer performance than do low-contextual interference situations. One hypothesis for this phenomenon is that high-contextual practice situations result in a more detailed and elaborate memory representation of the learned motor skill (Shea & Morgan, 1979). In other words, variable practice allows the learner to compare and contrast the variations in movement, allowing for a robust memory representation of the skill that can be more readily accessed at a later time. An alternate hypothesis is that in variable practice situations, the learner must actively engage in problem solving on every new skill attempt, whereas in a low-contextual practice situation, little, if any, problem solving is required because the situations do not change significantly across trials (Lee & Magill, 1985). It is believed that the act of having to actively engage in problem solving due to the intervening practice variability leads the learner to reconstruct a more robust action plan. Although the mechanisms proposed in each hypothesis are different, both share the basic idea that the learner's memory trace or action plan is enhanced by variability in the practice situation. In the change/no-change procedure, it is possible that the perceptual representation of the stimuli also could be enhanced by multiple opportunities to perceive the contrast between the speech stimuli. In other words, the context in which the standard or comparison stimulus is presented is variable in the sense that contrasting stimuli are presented on intervening trials, rather than all of the standards being presented together followed by all of the comparisons. Note that this likely reflects less context variability than typically is used in motor-learning studies, but certainly more than has been used previously in the change/no-change procedure. Perhaps increased exposure to the variability between the stimuli also will lead to a more robust and detailed memory trace of the stimuli and enhanced discrimination due to more opportunities to compare and contrast the stimulus pairs.

The purpose of the present investigation was to determine whether both routes—sequential and alternating repetitions of stimuli—provide equally enhanced speech discrimination or whether one leads to more robust discrimination than the other. If only the sequential repetition of individual stimuli facilitates discrimination sensitivity, then enhancing the representation of the speech stimuli through straightforward sequential repetition would be the locus of the advantage of multiple stimuli repetitions in speech-sound discrimination. If both sequential and alternating types of repetition facilitate discrimination sensitivity, the results would suggest that there are multiple routes to enhancing the ability to detect differences between speech stimuli, but one could potentially provide a larger advantage than the other. If sequential repetitions lead to better discrimination than alternating repetitions, then this would suggest that the internal representation is strengthened best when the system can sample each stimulus in succession without potentially interfering input. Additionally, the opportunity to contrast the stimuli multiple times is not as important for forming a robust internal representation as having sequential opportunities to process the stimuli. On the other hand, if alternating repetitions lead to better discrimination than sequential repetitions, then this would suggest not only that the internal representation is not hurt by interfering stimulus presentations but also that the opportunity to compare and contrast the stimuli multiple times enhances the representation beyond that achieved through straightforward repetition of the stimuli themselves.

Method

Participants

Twenty-three adults were recruited to participate in this investigation. Three were unable to return to the lab for all of the research visits. Therefore, 20 participants completed the entire protocol. Only their data were used in the subsequent analyses. The participants ranged in age between 19 and 38 years (M = 23.2 years); 14 of them were female, and 6 of them were male. Participants were native English speakers and passed a hearing screening at 20 dB HL for audiometric frequencies between and including 500 Hz and 8000 Hz, and 25 dB HL at 250 Hz (re: American National Standards Institute, 2004).

Stimuli

Three pairs of nonsense, digitized, natural consonant–vowel syllables were used as stimuli: /pa/ versus /ta/, /ra/ versus /la/, and /sa/ versus /ʃa/. These three contrast pairs were selected for several reasons: (a) nonsense syllables were selected rather than real words to reduce lexical influences on the task; (b) within a contrast pair, the syllables differ in place of articulation—which is known to be a difficult contrast to perceive, even in listeners with normal hearing (Miller & Nicely, 1955)—while varying in manner of articulation across contrast pairs; (c) the fricative–vowel stimuli have been studied extensively by Nittrouer and colleagues, who demonstrated developmental changes in speech perception with them (e.g., Nittrouer, 1992, 1996; Nittrouer, Manning, & Meyer, 1993; Nittrouer & Miller, 1997); and (d) synthetic versions of the stimuli have been used in previous investigations (Holt & Carney, 2005, 2007).

The stimuli were recorded from a young, Caucasian female who spoke a General American dialect of English. The single recording session took place inside a double-walled soundbooth using a Sennheiser head-mounted condenser microphone and a Marantz digital recorder using a 16-bit, 44.1-kHz sampling rate. All files were saved in a .wav format. The speaker was instructed to use a pleasant voice, breathe between tokens, and utter each item such that the items were approximately the same length and intensity. During the recording, the speaker was asked to say each individual syllable about 10 times before moving on to the next one. The experimenter kept track of how many good tokens were uttered and, once 10 were accumulated, asked the speaker to move on to the next syllable. After all six syllables were recorded at least 10 times, the length of each token was measured to verify that the members of each pair were relatively similar in duration to one another. Then, seven more sets of approximately 10 tokens per syllable were recorded. More than 80 recordings were made of each syllable so that (a) there were many from which to select during a stimulus rating procedure and (b) multiple tokens of each could be used as the final selected stimuli. The advantage of using natural tokens is that listeners have access to a rich signal with all the cues typically available during speech perception; the potential drawback is that there is less control over each stimulus. Using multiple tokens for stimuli nearly eliminates the possibility that listeners will rely on unanticipated subphonemic cues from any given token. The tokens were spliced out of the large .wav files, the total root-mean-square (RMS) of the retained tokens were equalized, and each of their lengths was measured in Adobe Audition software (Version 2.0; Adobe Systems, 2005). Only those tokens that had durations within 50 ms of the mean and that were free of any extra noises (e.g., audible lip smacking) were selected for use in the stimulus rating procedure, leaving 64 /pa/, 57 /ta/, 72 /ra/, 42 /la/, 64 /sa/, and 70 /ʃa/ possible stimuli.

To select the best tokens of each syllable for use in the discrimination experiment, a stimulus rating procedure was carried out. All of the equalized tokens were presented at an average RMS of 65 dB A to 10 adults with normal hearing (age range: 19–24 years; *M* = 22.3 years) in the sound field. Listeners were seated in front of a touchscreen monitor on which instructions and the user interface appeared. The participants were told to listen to each syllable while an orthographic representation of the given syllable appeared on the monitor. After each token was presented, an integer scale with numbered boxes from 1 through 7 appeared on the screen. On the far left, Box 1 was labeled a "poor example of the syllable" and on the far right, Box 7 was labeled a "good example of the syllable." Participants were told to register their response by touching one of the boxes on the scale, thereby indicating how well they felt that each presented token exemplified the intended syllable. Stimuli were presented in random order to the participants, and all participants listened to a single presentation of each stimulus. The 20 tokens of each syllable with the highest average ratings were selected for use in the discrimination study. Mean ratings, *SD*s, average median ratings, and mean durations for each syllable are provided in Table 1. All the average ratings of the tokens used were high: The lowest mean rating was for /ta/ (5.8 of a possible 7.0), and the highest was for /ʃa/ (6.4 of a possible 7.0). The median scores were even higher (all were 6.1 or higher of a possible 7.0), reflecting that the majority of individual ratings were actually higher than the mean rating. The rating results suggest that the selected 20 tokens of each syllable were perceived as good examples of the intended targets.

Table 1. Descriptive data for the stimuli selected for use in the discrimination procedure.

Syllable	Rating *M (SD)*	Average median rating	Duration *M (SD)*
/pa/	6.3 (0.95)	6.9	457 ms (25 ms)
/ta/	5.8 (1.30)	6.1	447 ms (28 ms)
/ra/	6.1 (1.16)	6.6	453 ms (26 ms)
/la/	6.2 (1.18)	6.7	452 ms (25 ms)
/sa/	6.3 (1.02)	6.9	545 ms (22 ms)
/ʃa/	6.4 (0.87)	6.7	526 ms (25 ms)

With natural stimuli, there is some variability in the duration of individual tokens, although the average durations of the tokens for each pair were relatively similar, as were the *SD*s. For the stop-consonant pair, the average difference in duration between the /pa/ and /ta/ tokens was 10 ms (mean /pa/ duration: 457 ms; mean /ta/ duration: 447 ms). Additionally, the *SD*s were similar (25 ms for /pa/; 28 ms for /ta/). For the liquid pair, the average difference in duration between the /ra/ and /la/ tokens was just 1 ms (mean /ra/ duration: 453 ms; mean /la/ duration: 452 ms), and the *SD*s were similar (26 ms for /ra/; 25 ms for /la/). Finally, for the fricative pair, the average difference in duration between the /sa/ and /ʃa/ tokens was 19 ms (mean /sa/ duration: 545 ms; mean /ʃa/ duration: 526 ms), and the *SD*s were similar, as well (22 ms for /sa/; 25 ms for /ʃa/). Therefore, the 20 selected tokens were relatively similar in length within each contrast, although there was a slightly greater difference in the relative durations of the fricative pair than in the other two contrasts.

Within each speech-sound contrast, the 20 selected tokens of each syllable were randomly paired with one another to achieve the desired sets of stimulus repetitions. For each trial type, five different sets of tokens were used. For example, for the 2-repetition sequential liquid contrast condition in which /ra/ was the standard, there were five different randomizations of the /ra/ and /la/ tokens for the change trials and five different randomizations of /ra/ tokens for the no-change trials. The interstimulus interval was 100 ms.

For the discrimination procedure, the overall level of the speech was 65 dB A at the listener's head. Calibration was checked daily. To limit ceiling effects, participants were tested in white noise that was shaped to have the same long-term spectrum as each syllable pair. A random sample of a 10-s noise created for each syllable pair was amplified to achieve the desired SNR and was then mixed with the speech in Adobe Audition. Based on previous experience with synthetic versions of these syllables, the SNRs used were –10 dB, –8 dB, and –6 dB. The noise began and ended 100 ms before and after the syllables.

Equipment

Both the rating and discrimination procedures were run and the data collected on a Pentium computer using E-Prime software (Version 1.2; Psychology Software Tools, 2007). The signal was routed from the computer's sound card through a GSI-61 audiometer to two GSI speakers placed at ± 45° azimuth relative to the listener in a double-walled sound booth. A 19-in. ELO touchscreen monitor was placed approximately 18 in. in front of the listener's head. The instructions were presented via the user interface on the touchscreen monitor.

Procedure

The participants were run in a repeated-measures design with four factors: repetition type (sequential and alternating); SNR (–10, –8, and –6 dB); syllable contrast (stop-consonant, liquid, and fricative); and number of repetitions of stimuli (1, 2, and 4). Note that the 1-repetition condition for the both the sequential and alternating conditions was identical. Therefore, the 1-repetition condition was presented once. The 2-repetition and 4-repetition sequential conditions consisted of trials in which the standard was presented multiple times followed by repetitions of the comparison stimulus. For example, in the 2-repetition sequential condition in which the standard is /ra/ and the comparison is /la/, a change trial would consist of /ra ra la la/, and a no-change trial would be composed of /ra ra ra ra/. In contrast, the 2-repetition and 4-repetition alternating conditions consisted of trials in which the standard and comparison stimuli alternated multiple times. For example, in the 2-repetition alternating condition in which the standard is /ra/ and the comparison is /la/, a change trial would consist of /ra la ra la/, and a no-change trial would consist of /ra ra ra ra/. It is important to note that the total number of stimuli in a given trial for the 1-repetition condition was 2, for the 2-repetition sequential and 2-repetition alternating conditions was 4, and for the 4-repetition sequential and 4-repetition alternating conditions was 8. In other words, the total number of stimulus repetitions per trial was always held consistent across the two types of stimulus repetition conditions.

The stimuli were blocked by syllable pair, with the order of syllable pair randomly presented. Half of the participants were presented with one member of the stimulus pair as the standard; the other half were presented with the alternate member of the pair as the standard. Within the syllable pair, the order of the five stimulus repetition conditions was randomized and then within repetition condition, SNR was randomized. Each condition consisted of 50 trials, half of which were change trials and half of which were no-change trials. On each day of testing, all conditions for one syllable pair comparison were completed, resulting in three 2-hr visits for each participant. Before testing began, all listeners completed a pre-test consisting of 30 trials in quiet of either the 2-repetition sequential or 2-repetition alternating condition (depending on which repetition condition a given participant's randomization called for testing first) in the syllable pair they received that day. Feedback was provided during the 30 pre-test trials but not during the test trials. To ensure that listeners understood the task and that the stimuli could be reliably discriminated, we required all listeners to achieve 18 correct of the final 20 pre-test trials in order to proceed with testing in noise. All listeners achieved this criterion without exception.

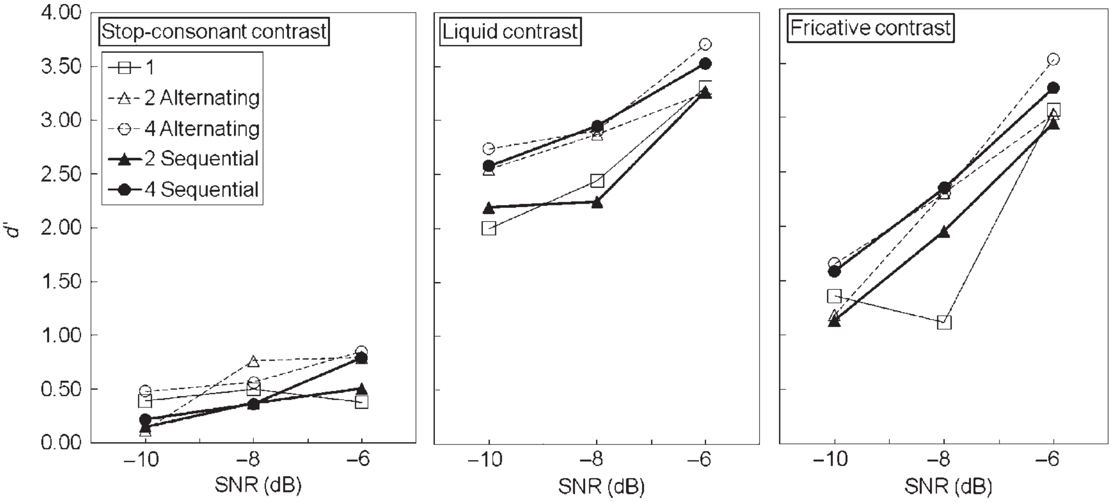
During testing, participants were seated in front of the touchscreen monitor on which the left side of the screen displayed a large rectangle labeled "Change" and the right side displayed an identical rectangle labeled "No Change." At the beginning of the study, participants were told to listen to the string of syllables and to touch the box labeled "Change" if they perceived the syllable string changing and to touch "No Change" if they did not detect a change in the syllable array. Before each condition, written instructions also appeared on the touchscreen monitor describing how many of each stimulus would be presented and what to do if she/he heard a change or no change in the syllable array. In addition to receiving the instructions orally from the experimenter, participants were told to read the instructions before each condition and to touch the screen when they were ready to begin.

Results

Performance was measured in d'. Average performance is displayed at each SNR as a function of the type of repetition procedure (sequential or alternating) and repetition number (1, 2, or 4) for each syllable contrast in Figure 1. The data for the stop-consonant contrast appear in the left panel, those for the liquid pair are displayed in the middle panel, and data for the fricative pair appear in the right panel.

The data were entered into a four-way analysis of variance (ANOVA) with repeated measures (factors: type of repetition [sequential, alternating], syllable contrast [stop, liquid, fricative], SNR [–10, –8, –6 dB], and number of stimulus repetitions [2, 4]). The 1-repetition condition was omitted from the analysis because the

Figure 1. Mean *d′* performance across signal-to-noise ratio (SNR) as a function of repetition procedure and repetition number for the stop-consonant contrast, /pa/ versus /ta/ (left panel); the liquid contrast, /ra/ versus /la/ (center panel); and the fricative contrast, /sa/ versus /ʃa/ (right panel). The sequential repetition conditions are indicated by solid lines and filled symbols, whereas the alternating repetition conditions are indicated by dashed lines and open symbols. The squares represent the 1-repetition condition, the triangles represent the 2-repetition condition, and the circles represent the 4-repetition condition.



1-repetition condition for the sequential and alternating procedures is identical. A summary of the statistically significant results of the four-way ANOVA appear in Table 2. Consistent with what can be observed in Figure 1, performance varied significantly across the three syllable contrasts, $F(2, 38) = 113.045$, $p < .0001$, with lower scores observed for the stop-consonant contrast than for the liquid or fricative contrasts. As expected, average performance improved with increasing SNR, $F(2, 38) = 108.163$, $p < .0001$. However, there was an interaction between SNR and syllable contrast, $F(4, 76) = 20.853$, $p < .0001$, reflecting the consistent finding that many participants had a great deal of difficulty discriminating the stop-consonant pair, but not the liquid or fricative pairs, regardless of the SNR, even though in quiet, all participants were able to discriminate all three sets of speech contrasts with high accuracy. Although follow-up three-way ANOVAs with repeated measures on the data from each syllable contrast revealed that performance improved for more advantageous SNRs for all three syllable contrasts—stop-consonants, $F(2, 38) = 16.464$, $p < .0001$; liquids, $F(2, 38) = 25.802$, $p < .0001$; and fricatives, $F(2, 38) = 123.148$, $p < .0001$—the psychometric functions for the liquid and fricative contrasts were certainly steeper than they were for the stop-consonant contrast. A summary of the follow-up three-way ANOVA results appears in Table 3.

Table 2. Four-way analysis of variance (ANOVA) with repeated-measures results, with data from the 1-repetition condition excluded.

Significant effects	*F*	*p*
Type of repetition	*F*(1, 19) = 9.62	.006
Syllable contrast	*F*(2, 38) = 113.05	< .0001
SNR	*F*(2, 38) = 108.16	< .0001
Repetition number	*F*(1, 19) = 23.53	< .0001
SNR × Syllable Contrast	*F*(4, 76) = 20.85	< .0001
Type of Repetition × Repetition Number × SNR	*F*(2, 38) = 3.27	.036

Note. SNR = signal-to-noise ratio.

Table 3. Follow-up three-way ANOVAs with repeated-measures results, with data from the 1-repetition condition excluded.

Variable	*F*	*p*
Stop-consonant contrast		
Significant effects		
Type of repetition	*F*(1, 19) = 8.36	.009
SNR	*F*(2, 38) = 16.46	< .0001
Liquid contrast		
Significant effects		
Repetition number	*F*(1, 19) = 9.19	.007
SNR	*F*(2, 38) = 25.80	< .0001
Fricative contrast		
Significant effects		
Repetition number	*F*(1, 19) = 14.73	.001
SNR	*F*(2, 38) = 123.15	< .0001

In the overall four-way ANOVA, the number of stimulus repetitions was also significant, $F(1, 19) = 23.533$, $p < .0001$. Although there was no interaction between number of stimulus repetitions and syllable contrast, the follow-up three-way ANOVAs revealed that more stimulus repetitions significantly improved liquid discrimination, $F(1, 19) = 9.187$, $p = .007$, and fricative discrimination, $F(1, 19) = 14.734$, $p = .001$, but not stop-consonant discrimination ($p = .268$).

The factor of primary interest in this investigation was the type of stimulus repetition. The overall ANOVA revealed that the type of repetition significantly influenced speech-sound discrimination, $F(1, 19) = 9.617$, $p = .006$. However, in the follow-up ANOVAs, the type of repetition influenced only stop-consonant discrimination, $F(1, 19) = 8.362$, $p = .009$, not discrimination of the liquid or fricative contrasts (ps = .124 and .186, respectively). Still, scores were near the floor for most repetition conditions, even at the most advantageous SNR for the stop-consonant contrast, thereby limiting the interpretation of these results. Figure 2 displays individual d' difference scores between the 2-repetition alternating and 2-repetition sequential conditions across SNR. Each panel displays data for one of the three syllable contrasts. Difference scores were calculated by subtracting the sequential score from the alternating score such that positive difference scores reflect higher performance in the alternating than in the sequential condition; the converse is true of the negative difference scores. Figure 3 displays difference scores for the 4-repetition conditions. The d' difference data suggest that overall, there is little evidence that one type of repetition promotes better discrimination than the other. The only exception to this is in the case of the 2-repetition conditions at –8 dB SNR, where there is an advantage for the alternating type of repetition (this will be discussed further in the next section). These data also suggest that although the average participant does not typically show an advantage for one type of repetition over another, some (although certainly not most) individual participants do demonstrate such an advantage, to some extent. For example, Participant 911 showed an advantage for the alternating type of repetition, whereas Participant 915 displayed an advantage for the sequential type of repetition across most conditions.

In the overall ANOVA, there was a significant three-way interaction between type of repetition, repetition number, and SNR, $F(2, 38) = 3.272$, $p = .036$. The interaction is displayed in Figure 4, in which each of the 2- and 4-repetition conditions is displayed as a function of SNR, collapsed across syllable contrast. This interaction reflects the finding that the effect of type of repetition was apparent only for the 2-repetition condition at –8 dB SNR. Under these conditions, the alternating type of stimulus repetition resulted in better performance than did the sequential type of repetition. The consequences of the interaction are also apparent in Figure 2, in which the d' difference scores for the 2-repetition conditions primarily are positive at –8 dB SNR but otherwise are equally distributed over the y-axis. Together, these results suggest that more stimulus repetitions improved discrimination but that the type of repetition seemed to be of less importance than presenting multiple opportunities to perceive the stimuli. Where differences emerged (e.g., at –8 dB SNR for the 2-repetition condition), the alternating type of repetition resulted in better performance than did the sequential. Overall, however, it appeared that listeners benefited from additional repetitions of the liquid and fricative contrasts, regardless of whether they were presented sequentially or in an alternating fashion.

In summary, each of the main effects (type of repetition, syllable contrast, SNR, and repetition number) in the overall four-way ANOVA significantly influenced discrimination ability. Further, with data from the 1-repetition condition removed from the analyses, only two interactions were significant. The interactions were further explored by evaluating follow-up three-way ANOVAs on the data from each syllable contrast. The follow-up analyses revealed that more repetitions of stimuli improved discrimination of the liquid and fricative, but not the stop-consonant, contrasts. Further, the effect of type of repetition was being carried by the stop-consonant contrast; however, this was due to little variability in the scores near the floor for this contrast and thus appears to be an artifact. Finally, the effect of repetition type was minimal and limited: The type of repetition influenced discrimination only for the 2-repetition condition near the midpoint of the psychometric function; otherwise, the effect of repetition type was negligible across the syllable contrasts, numbers of repetitions, and SNRs.

Discussion

The purpose of this study was to investigate the locus for the observed advantage for enhanced speech discrimination with multiple stimulus repetitions. Two possible explanations were explored: The first proposed explanation was that when stimuli are presented sequentially (e.g., /ra ra la la/), the listener is able to form more robust and detailed representations of that signal in memory, resulting in improved discrimination from a novel stimulus; the second proposed explanation was that discrimination could be improved by highlighting the differences between the stimuli by offering multiple opportunities to perceive the contrast itself (e.g., /ra la ra la/).

The results from the present investigation suggest that although increasing the number of stimulus repetitions

Figure 2. Individual *d′* difference scores between the 2-repetition alternating and 2-repetition sequential conditions across SNR. The top panel displays data for the stop-consonant contrast, the middle panel displays data for the liquid contrast, and the bottom panel displays data for the fricative contrast.

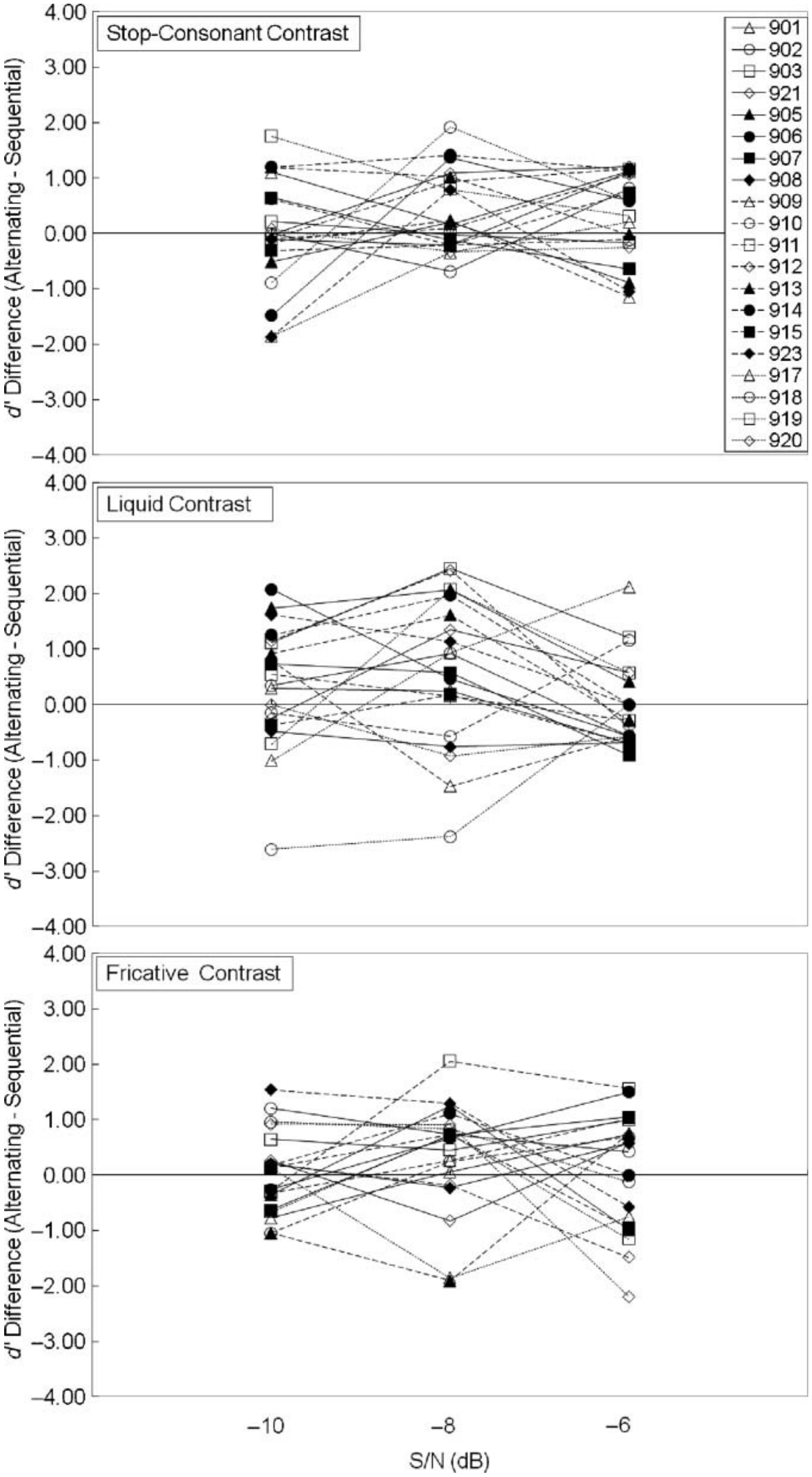


Figure 3. Individual *d′* difference scores between the 4-repetition alternating and 4-repetition sequential conditions across SNR. The top panel displays data for the stop-consonant contrast, the middle panel displays data for the liquid contrast, and the bottom panel displays data for the fricative contrast.

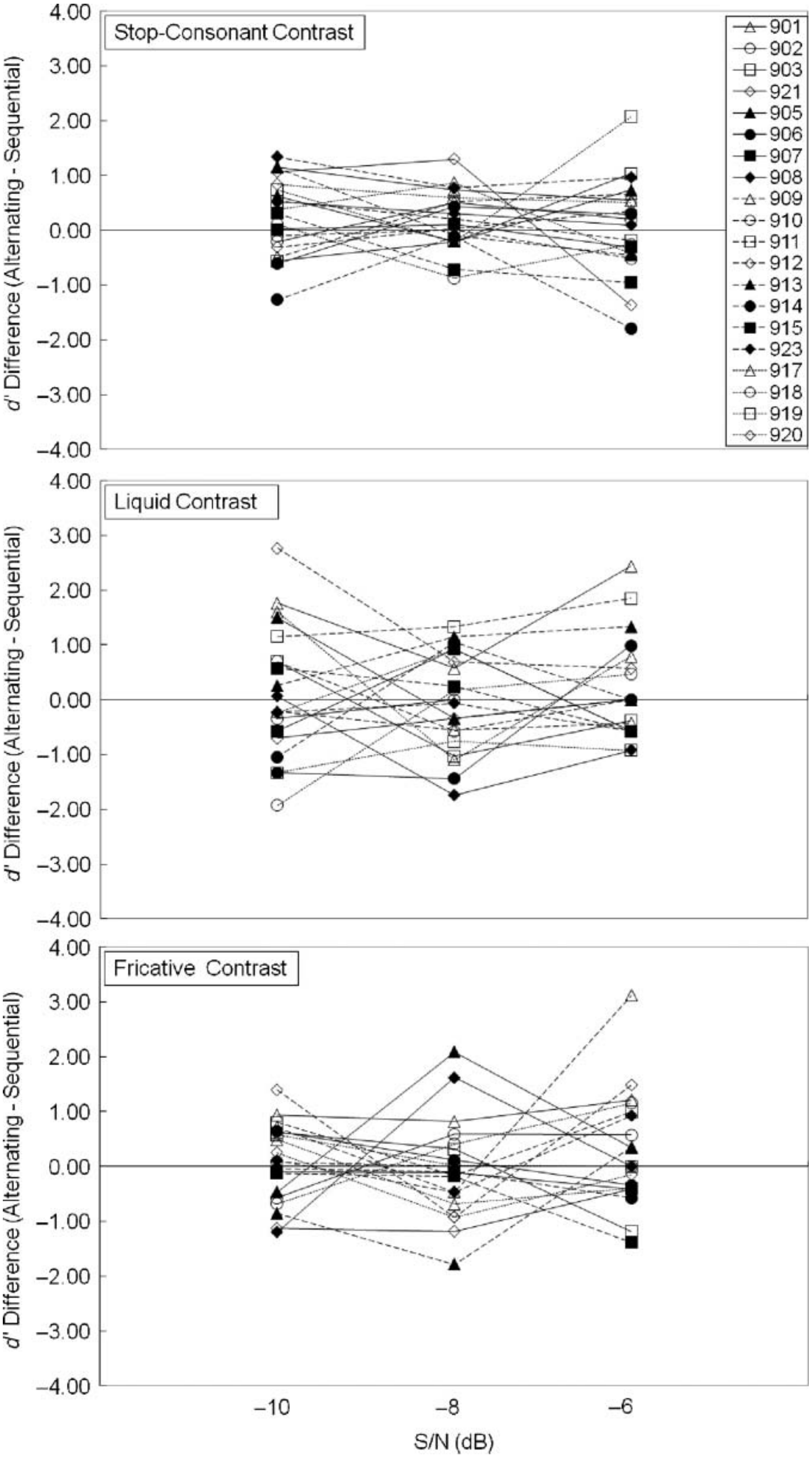
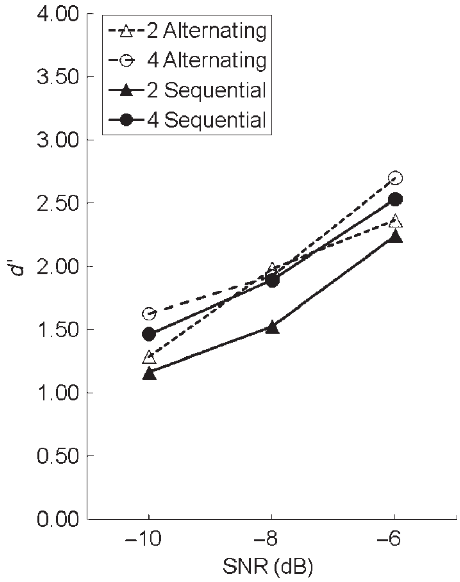


Figure 4. Mean *d′* performance collapsed across syllable contrast and displayed across SNR as a function of the type of repetition procedure. The sequential repetition conditions are indicated by solid lines and filled symbols, whereas the alternating repetition conditions are indicated by dashed lines and open symbols. The triangles represent the 2-repetition condition, and the circles represent the 4-repetition condition.



improves discrimination of liquid and fricative stimuli (thereby supporting and extending Holt & Carney's [2005, 2007] findings to natural stimuli), the method by which the stimuli are repeated (sequential or alternating) does not differentially effect performance in any broad sense under the conditions tested in the present investigation. Although the effect of stimulus repetition type was significant in the overall ANOVA, the follow-up analyses revealed that the effect was being carried by the stop-consonant contrast in which the scores were near the floor and thus is likely an artifact. The only occasion in which there was an advantage for one type of stimulus repetition over the other was for the 2-repetition alternating condition near the midpoint of the psychometric function—at –8 dB SNR. This pattern of results did not appear for any other SNR or for any of the 4-repetition conditions.

The common finding between both stimulus repetition types is that more repetitions of stimuli improve discrimination to nearly the same degree. If there is an advantage, it is under specific conditions for the alternating type of repetition. Although the repetitions in the alternating conditions were conceived of as being a repetition of the contrast or the change between the standard and comparison, the stimuli themselves by definition also were being repeated (just not in direct succession). Thus, the key to improved discrimination appears to be multiple stimulus repetitions, regardless of whether the string of standards is periodically "interrupted" with, or contrasted to, tokens of the comparison stimulus. In other words, the representation of a stimulus can be enhanced with sequential repetitions (as was initially posited in earlier work) but also with alternating repetitions. These results can be interpreted in the following ways:

1. Presenting intervening stimuli does not significantly interfere with the robustness of the representation—which is consistent, to some extent, with the repetition priming and repetition suppression literature, in which effects are seen even with intervening stimuli and time delays in stimulus presentation (see, e.g., Forbach et al., 1974; Grant & Logan, 1993; Graves et al., 2008; Huber, 2008; Huber, Tian, Curran, O'Reilly, & Woroch, 2008; James & Gauthier, 2006; Orfanidou et al., 2006; Rauschecker et al., 2007).
2. Little is gained in strengthening the representation by providing multiple opportunities to directly and overtly compare and contrast the stimuli beyond that offered by straightforward sequential repetition of stimuli.
3. Whatever, if anything, is lost by interrupting the formation of a robust representation with alternating stimulus presentation is replaced by what is gained by comparing and contrasting the stimuli. The current investigation was not designed to address these competing interpretations of the findings, but future investigations could begin teasing them apart.

The limited effect of type of repetition was found despite the fact that in the alternating procedure, there are even more opportunities to compare and contrast the stimuli than there are to successively perceive the stimuli in the sequential procedure. For example, in the 4-repetition sequential condition (e.g., /ra ra ra ra la la la la/), listeners have four opportunities to encode and process the /ra/, followed by four opportunities to encode and process the /la/, and one opportunity to overtly contrast them (although listeners certainly could be—and probably are—contrasting each subsequent presentation of the comparison to the internal representation formed of the standard). In the 4-repetition alternating condition (e.g., /ra la ra la ra la ra la/), which was designed to be equivalent to the 4-repetition sequential condition, the total number of presentations of /ra/ and /la/ was exactly the same as that in the sequential condition, but the number of times the standard stimulus (/ra/, in this example) changed to the comparison stimulus (/la/, in this example) was four. In this condition, the listener actually has more than four opportunities to compare and contrast the stimuli because the comparison changes back to the standard three times. In fact, the listener has seven opportunities to overtly compare and contrast the standard and comparison stimuli in the 4-repetition alternating condition, in addition to having four opportunities to encode and process both the standard and the comparison (although the opportunities to encode each are interrupted by the presentation of the alternate stimulus). Likewise, in the 2-repetition alternating condition (e.g., /ra la ra la/), there are actually three opportunities to overtly compare and contrast the difference between the stimuli: two in which the standard changes to the comparison stimulus and one in which the comparison changes to the standard. In the 1-repetition condition, there is a single opportunity to detect the change. Therefore, despite having even more opportunities to overtly compare and contrast the standard and comparison stimuli in the 2- and 4-repetition alternating conditions, there was only one condition in which any advantage appeared: the 2-repetition condition near the midpoint of the psychometric function where the stimuli were sufficiently audible—above discrimination threshold—but not at ceiling. The present study controlled for total number of stimulus presentations per trial across complimentary types of repetition—an important control for investigating the effect of stimulus repetition. However, with some understanding of the effect of different types of repetition with this control in place, it might be fruitful in future work to ignore the total number of stimuli presented on each trial and to directly compare number of sequential repetitions to number of changes between the contrasting stimuli (e.g., compare /ra ra la la/ to /ra la ra/). This type of investigation would address observations made here and would begin teasing apart possible interpretations of the results, which were discussed earlier.

It is not surprising that performance varied across the syllable pairs (and thus by manner of articulation). Work by Boothroyd, Erickson, and Medwetsky (1994) on audibility of individual consonants predicts differences in discrimination across the syllables. However, this is the third investigation of its kind to fail to demonstrate improvement in stop-consonant discrimination using multiple stimulus presentations, despite the present study's use of natural speech tokens and an additional type of stimulus repetition. In the present investigation, stop-consonant discrimination performance improved slightly, although significantly, with SNR, but for the most part was near the floor regardless of the SNR. Holt and Carney (2005) used the same SNRs that were employed in this study, along with one additional, more advantageous one, –4 dB. Discrimination of the stop-consonant contrast at the more advantageous SNRs was better than it was in the present investigation, and yet they still failed to show that multiple repetitions of synthetic /pa/ and /ta/ stimuli improved adults' stop-consonant discrimination (reanalyzed in Holt & Carney, 2007). Future investigations could evaluate whether natural tokens or even other stop-consonants (e.g., /ba/, /ga/) at more advantageous SNRs could result in enhanced stop-consonant discrimination with multiple stimulus repetitions. Perhaps improved audibility combined with natural stimuli would allow for the effect to emerge as it did for liquid and fricative contrasts. The primary acoustic cues for discriminating the stop-consonant pair are the second and third formant transitions, which both increase for /pa/ and decrease for /ta/ due to the relative frequency content of their respective bursts. The formant transitions for the stop-consonant contrast occurred over a shorter time interval (less than 60 ms) than the primary cues for the liquid contrast—the relative third formant transitions (which were longer than 100 ms in duration), and the fricatives—their relative noise spectra bandwidths (which also were longer than 100 ms in duration). Perhaps listeners require a more audible signal to capitalize on the more transient acoustic aspects of the stop-consonant contrast with multiple stimulus repetitions.

In summary, the results of this investigation support our previous work demonstrating that increasing the number of stimulus presentations allows listeners to form a more robust and highly detailed representation of the signal in short-term memory and to better discriminate between liquid and fricative stimuli. More importantly, they suggest that this enhanced discrimination can be attained with two different types of stimulus repetitions. With robust, highly detailed representations of a stimulus in short-term memory, the listener is able to more accurately detect that the stimulus is different from a novel one. Providing listeners with multiple opportunities to overtly and directly compare and contrast the stimuli might lead to even better discrimination for low numbers of sufficiently audible stimulus repetitions than for sequential stimulus repetitions. However, overall, the multiple repetition effect is robust enough to apply to these two different types of stimulus repetition.

It is believed that many clinical populations have a core deficit in rapid phonological encoding skills, such as children with hearing loss who use hearing aids and/or cochlear implants (e.g., Miller, 1997; Spencer & Tomblin, 2008), children with specific language impairment (e.g., Coady & Evans, 2008; Gathercole & Baddeley, 1990), children experiencing reading deficits (Snowling, 2000; Snowling, Bishop, & Stothard, 2000), and second-language learners (e.g., Hu, 2008; Papagno, Valentine, & Baddeley, 1991). Even adults with hearing loss who use hearing aids show deficits in their ability to rapidly perform phonological coding operations (Andersson, 2002). Demonstrating that the strength of the stimulus representation at the initial point of entry to speech-sound processing can be evaluated using this behavioral methodology in adults is an important first step in opening up other research possibilities for understanding how speech sounds are initially encoded, stored, and maintained in auditory short-term memory by children, particularly those with a wide range of delays or disorders. A fundamental disturbance in early sensory encoding can propagate to higher-level processing, having far-reaching effects on spoken language development and language processing (Luria, 1973). Further, understanding the early sensory and phonological encoding of speech sounds has clinical implications for developing novel therapies to reduce or eliminate the negative effects of speech-sound processing deficits. For example, initial findings by Pisoni and Cleary (2004) and Cleary, Pisoni, and Geers (2001) and more recent work by Conway, Pisoni, Anaya, Karpicke, and Henning (2011) demonstrated that children with cochlear implants might have disturbances and/or delays in processing, encoding, storing, and retrieving sequential repetitions of both auditory and visual patterns. These deficits result in children who are deaf with cochlear implants benefiting less than NH children from multimodal (auditory, visual, and audiovisual) pattern sequence repetition in a learning paradigm (Conway et al.; Pisoni & Cleary). These findings suggest that, in addition to a hearing impairment, some children who are deaf with cochlear implants also might have fundamental domain-general learning deficits that cause them to capitalize less on pattern repetition than their NH peers. Further, efficient encoding and rehearsal of phonological sequences appear to be important prerequisites for language learning (e.g., Conway & Pisoni, 2008). Therefore, having a tool such as the change/no-change procedure could be valuable for assessing how robust—or, in some cases, fragile—the early representations are, particularly in clinical populations suspected of having deficits in this area. Identifying deficits in early sensory encoding is an important step in providing a complete diagnostic picture of a given child because fundamental disturbances in this early stage of speech-sound processing can have detrimental cascading effects on higher-level speech and language processes and may impact later literacy and academic performance (Geers, 2003).

There is preliminary evidence that NH children benefit from sequential repetitions in discriminating synthetic fricative–natural vowel syllables (Holt & Carney, 2007). If future research demonstrates broader effects of stimulus repetition to contrasts with other manners of articulation through the use of natural stimuli in children, then follow-up work on whether they show discrimination with one type of repetition over the other would be warranted. Previous data suggest that adults and children weight aspects of the speech signal differently in making perceptual judgments (Jusczyk, 1993; Nittrouer, 1992; Nittrouer et al., 1993). Therefore, it is possible that children might demonstrate a different pattern of results than adults. That the initial representation of speech signals could be strengthened with sequential and/or alternating repetitions would be an important finding in young children with less listening experience, especially if it were extended to children who are deaf with cochlear implants.

It also is possible that a better understanding of possible routes to enhanced speech-sound discrimination through stimulus repetition in children could have implications for intervention. Depending on whether children display effects for both types of stimulus repetitions (and if one type is more effective than the other) or just for the sequential type of repetition, future research could investigate whether training with multiple stimulus repetitions can ameliorate some of the deficits in phonological encoding displayed by many clinical pediatric populations.

Conclusions

The results of this investigation suggest that (a) adult listeners' discrimination of the fricative and liquid contrasts is enhanced with multiple stimulus repetitions; (b) both sequential and alternating types of repetition facilitate better discrimination performance, suggesting that the effect of stimulus repetition on speech-sound discrimination is robust enough to apply to two different types of stimulus repetitions; and (c) overall, sequential and alternating repetition types enhance discrimination to similar degrees, although in the limited conditions under which there was a difference, the alternating type of repetition resulted in better performance than did the sequential type of repetition. Future work will investigate possible explanations for why the stop-consonant contrast has been resistant to the effects of stimulus repetition and whether children display similar effects for the two types of stimulus repetitions as adults.

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